

**Nebular Fractionations and Mn-Cr Systematics.** P. Cassen<sup>1</sup> and D. S. Woolum<sup>2</sup>, <sup>1</sup>NASA-Ames Research Center, 245-3, Moffett Field, CA 94035; <sup>2</sup>Physics, Cal State Univ., Fullerton, CA 92634..

Evidence for live  $^{53}\text{Mn}$  has been found in calcium and aluminum rich inclusions (CAIs) in the Allende meteorite (1,2); an enstatite chondrite (Indarch) and a pallasite (Eagle Station) (2); the angrite LEW 86010 and the eucrites Chervony Kut and Juvinas (3,4,5); ordinary chondrites (6); and the Martian meteorites ALH84001 and Shergotty (6). Lugmair and et al. (6) have pointed out that there is a pattern of decreasing excess  $^{53}\text{Cr}$  (produced by the decay of  $^{53}\text{Mn}$ ) in the differentiated meteorites, chondrites, Mars and Earth, that is plausibly explained by a dependence of the abundance of  $^{53}\text{Mn}$  on radial distance from the Sun. They point out that such a nonuniform distribution could have been caused either by an intrinsically heterogeneous injection of  $^{53}\text{Mn}$  into the Solar System, or by an early, systematic fractionation of Mn relative to Cr. It is known that Mn/Cr in chondritic meteorites is fractionated relative to CI ("solar") abundance (7), so we have explored the consequences of such fractionations for  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  systematics in planetary bodies. The process we have in mind is the volatility controlled, sequential condensation and accumulation of solid material in a cooling nebula of diminishing mass. Quantitative models of this process can account for the general patterns of depletion of moderately volatile elements found in the carbonaceous meteorites (8). Here, we conclude that the apparent dependence of initial  $^{53}\text{Mn}$  abundance on distance from the Sun can be explained by Mn/Cr fractionations of the magnitude observed in the chondrites. This conclusion raises the possibility that  $^{53}\text{Cr}$  measurements can be used to further constrain models of nebula thermal evolution.

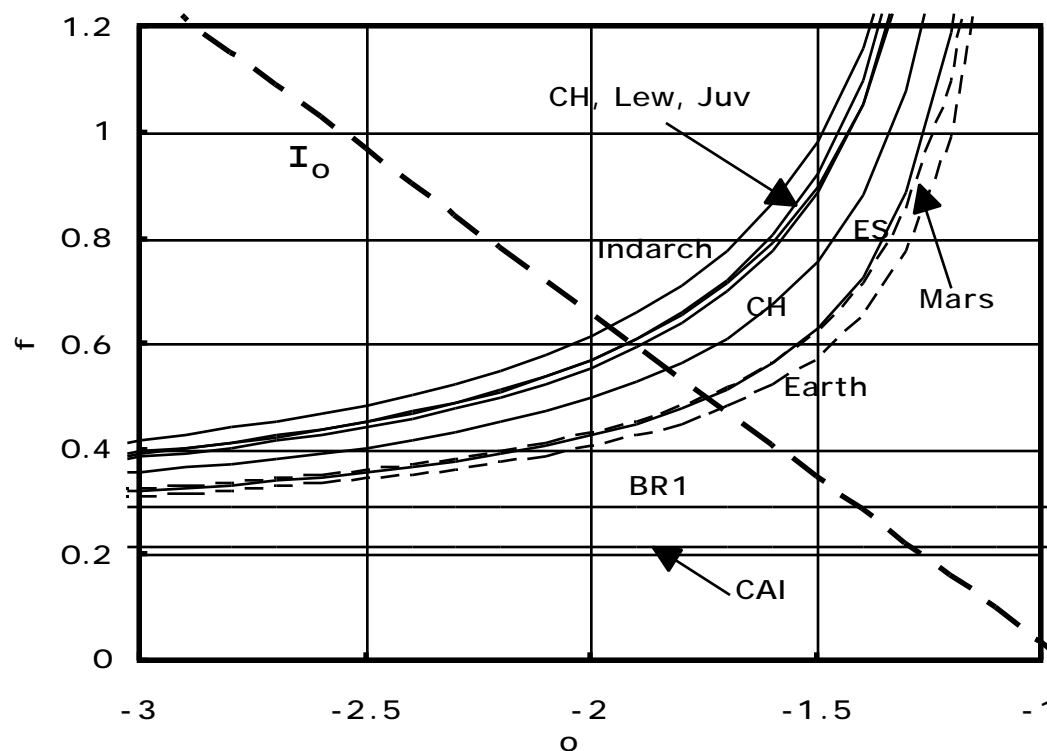
In the model under consideration, solid bodies accumulate from dust as it condenses and/or coagulates in the cooling nebula. Nebula cooling is promoted by coagulation itself (which reduces the optical depth and therefore enhances radiative losses), diminishing nebular mass (which also reduces the optical depth), and a decreasing release of gravitational energy as the accretion from the nebula onto the Sun slows. In the initially hot, inner regions of the nebula, an element begins to be accumulated only when nebula temperatures drop below its condensation temperature; thus the more refractory elements begin to accumulate first. Because the total nebular mass is decreasing (mainly by accretion onto the Sun), a growing planetary body, e.g., a meteorite parent body, accumulates systematically less volatile elements than refractory elements. Also, if CAIs represent early survivors of a hot nebula, they would be expected to be formed from volatile-deficient material. In general, discrete entities and isolated formed early, and planetary objects formed closer to the Sun, are both expected to have formed from more refractory compositions than late forming entities and objects formed further from the Sun. Models of coagulation in an evolving nebula (8) indicate that the regular depletions of moderately volatile elements (7) may be explained in such a way; however, the conclusions presented here rely only on the fact that Mn, which is somewhat more volatile than Cr (7), is observed to be depleted relative to Cr in chondritic meteorites.

We consider simple models for the thermal histories of the bodies with observed  $^{53}\text{Cr}$  excesses. Differentiated meteorites are assumed to be the products of parent bodies with modestly non-solar, nebula-fractionated bulk compositions, which underwent a single stage of melting and differentiation. A "standard" Allende CAI is presumed to have evolved as a closed system from some early time, and to possess  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  systematics as found by Birck and Allegre (1) for their set of whole rock inclusions. But their individually analyzed inclusion BR1 is assumed to have suffered a later thermal event (as would be required if its data do represent an isochron) some 3 million years later, during which its Mn/Cr ratio was also modified by exchange with an ambient medium. Earth and Mars equilibrated well after the decay of all  $^{53}\text{Mn}$  (3). We calculate  $I_0$  = the initial  $^{53}\text{Mn}/^{55}\text{Mn}$  as a function of  $I_0 = \text{initial} [(^{53}\text{Cr}/^{52}\text{Cr})/(^{53}\text{Cr}/^{52}\text{Cr})_{\text{ref}}] - 1$ , from the assumption that BR1 is derived from a "standard" Allende CAI. We then calculate the Mn/Cr

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fractionations for all bodies (as a function of  $\delta_o$ ) using the slopes and intercepts of their respective vs.  $^{55}\text{Mn}/^{52}\text{Cr}$  curves, as reported in the literature. The results are shown in the Figure ( $f$  is the CI-normalized Mn/Cr ratio).

From data in (7), carbonaceous chondrites,  $f = .79$ ; in enstatite chondrites,  $f = .94$ . Lugmair et al. (6) found  $f = .88$  (CI-normalized) for the bulk ordinary chondrites they examined. Note that these fractionations are attained for values of  $I_o = 4 \times 10^{-5}$  and  $\delta_o = -1.5$ . Note, further, that there is a systematic progression of fractionation inward from the differentiated meteorites, through the ordinary chondrites and Mars, to the Earth, as would be found in the nebular fractionation models described above. Finally, note that BR1 differs from CAI composition by a relative enhancement of Mn, as would be produced by the addition of a solar component. Thus, we conclude that the spatial dependence of  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  systematics found by Lugmair et al. can be explained by fractionation from an initially uniform nebula. The same conclusion can be reached using other models regarding the relationship of BR1 to other CAIs, or, in fact, by ignoring the CAIs altogether and determining  $I_o(\delta_o)$  from  $^{53}\text{Cr}/^{52}\text{Cr} - ^{55}\text{Mn}/^{52}\text{Cr}$  isochron of Indarch, and assuming that Indarch has typical enstatite Mn/Cr.



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